

Recent Advances in Ultrafast Laser Nanostructuring: S-waveplate and Eternal Data Storage

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Abstract: Ultrashort light pulses create self-assembled sub-wavelength structures in the bulk of silica glass. Recent progress in applications of this phenomenon ranging from polarization and vortex converters to 5D optical data storage is reviewed.

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Material processing with ultrafast lasers has attracted considerable interest due to new science and a wide range of applications from laser surgery, integrated optics and optofluidics to optical data storage, 3D micro- and nano-structuring [1]. A decade ago it has been discovered that under certain irradiation conditions self-organized sub-wavelength structures with features of 20 nm, smallest ever produced by light, can be created in the volume of silica glass [2,3]. These structures are formed of porous glass nanoplanes [4], which were shown to sustain temperatures of 1000°C [5]. The phenomenon of nanograting formation has attracted considerable interest with proposals of applications ranging from micro- and nano-fluidics [6] to polarization control devices [7]. Here we review recent applications of ultrafast laser self-assembled sub-wavelength structuring to fabrication of space-variant polarization and phase converters branded as the S-waveplates [8] and polarization multiplexed optical data storage with practically unlimited lifetime [9].



Figure 1. Femtosecond laser written S-waveplate in cross-polarized light.

The femtosecond laser written nanostructure exhibits form birefringence and acts as a micro-waveplate with the slow axis oriented perpendicular to the polarization of the laser beam. A uniform birefringent layer can be induced by continuously scanning the bulk of the glass with the laser beam. The additional control of the electric field orientation allows imprinting optical elements with spatially variant anisotropy, which can affect polarization and phase of the passing light. The S-waveplates (Southampton-Super-Structured-waveplates [10]) are one of the examples of such birefringent optical elements, which can be used for obtaining axially symmetric polarization state, e.g. radial or azimuthal (Fig. 1). The radial symmetry of the electric field exhibits interesting properties under tight focusing with generation of strong longitudinal component and sub-diffraction limited spot size. Alternatively, the same optical element can be used for generating optical beams with the phase singularity (optical vortexes). The applications of S-waveplates ranges from material processing to microscopy and optical trapping.

The high chemical and thermal resistance of nanogratings makes them an ideal choice for archival data storage with practically unlimited lifetime. The multilevel data encoding is implemented via intensity and polarization of the beam, which are imprinted into the structure of the self-assembled nanograting via its thickness and orientation.

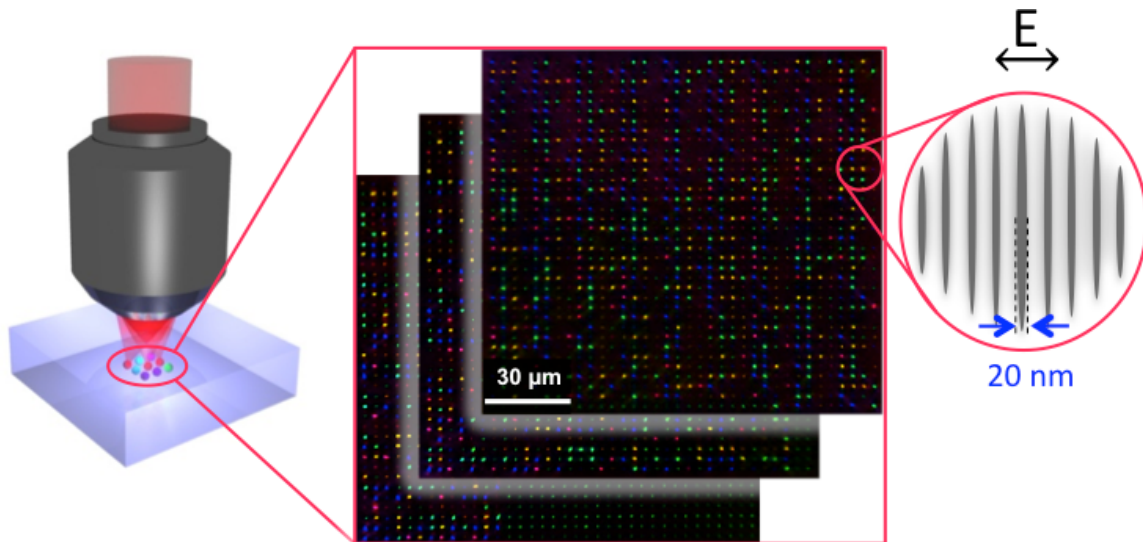


Figure 2. 5 dimensional optical storage. Each voxel contains a self-assembled nanograting oriented perpendicular to the electric field vector. The information is recorded in orientation and thickness of the nanostructure.

The digital document optically encrypted into five dimensions was successfully retrieved by nondestructive quantitative birefringence measurements. The recording time was reduced by two orders of magnitude implementing multiple beams recording technique, where simultaneously up to 100 birefringent dots could be imprinted with variable polarization and intensity (Fig. 2). Each dot contained 3 bits of information. The information was decoded by combining two binary data sets retrieved from the phase retardance and the slow axis orientation. Out of 11 664 bits, which were recorded in three layers, only 42 bit errors were obtained. By recording data with a 1.4 NA objective and shorter wavelength (250–350 nm), a disc with the capacity of 360 TB can be recorded. The accelerated aging experiments were performed to evaluate the stability of nanogratings at room temperature and estimate the activation energy of the nanovoids collapse. The decay time at lower temperatures was evaluated from the Arrhenius plot. At room temperature (303 K) the decay time of nanogratings is $3 \times 10^{20 \pm 1}$ years, indicating unprecedented high stability of nano-structures imprinted in fused quartz. Even at elevated temperatures of $T = 462$ K, the extrapolated decay time is comparable with the age of the Universe - 13.8 billion years. The recording of a digital document into highly stable optical memory is a vital step towards an eternal archive.

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